Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY
MNRAS **445**, 2836–2841 (2014) doi:10.1093/mnras/stu1956

A neutrino model fit to the CMB power spectrum

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Accepted 2014 September 18. Received 2014 September 1; in original form 2014 February 21

ABSTRACT

The standard cosmological model, Λ cold dark matter (ΛCDM), provides an excellent fit to cosmic microwave background (CMB) data. However, the model has well-known problems. For example, the cosmological constant, Λ, is fine-tuned to 1 part in 10^{100} and the CDM particle is not yet detected in the laboratory. Shanks previously investigated a model which assumed neither exotic particles nor a cosmological constant but instead postulated a low Hubble constant (H_0) to allow a baryon density compatible with inflation and zero spatial curvature. However, recent *Planck* results make it more difficult to reconcile such a model with CMB power spectra. Here, we relax the previous assumptions to assess the effects of assuming three active neutrinos of mass ≈5 eV. If we assume a low $H_0 \approx 45\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ then, compared to the previous purely baryonic model, we find a significantly improved fit to the first three peaks of the *Planck* power spectrum. Nevertheless, the goodness of fit is still significantly worse than for ΛCDM and would require appeal to unknown systematic effects for the fit ever to be considered acceptable. A further serious problem is that the amplitude of fluctuations is low ($\sigma_8 \approx 0.2$), making it difficult to form galaxies by the present day. This might then require seeds, perhaps from a primordial magnetic field, to be invoked for galaxy formation. These and other problems demonstrate the difficulties faced by models other than ΛCDM in fitting ever more precise cosmological data.

Key words: cosmology: observations – large-scale structure of Universe.

1 INTRODUCTION

The Λ cold dark matter (ΛCDM) model is highly successful at fitting the phenomenology of observational cosmology including the cosmic microwave background (CMB) and large-scale matter power spectra and these are highly important successes. However, the model suffers from problems at a more fundamental level. First, the size of the cosmological constant Λ implies a variety of fine tuning (Carroll 2001). For example, in the early Universe at the end of the inflationary epoch, the ratio of the vacuum energy implied by Λ to the energy in the radiation is 1 part in $\approx 10^{100}$. The vacuum energy of the cosmological constant can be replaced with dark energy whose density can evolve with time and thus alleviate this fine tuning. However, there still remains the coincidence of why the matter and dark energy densities reach equality so close to the present day. The dark matter component of the model also has the problem that the favoured candidate, the neutralino, is as yet undetected in the laboratory. The lower limits on supersymmetric particle masses such as the s-quark have reached >1 TeV at the Large Hadron Collider and almost rule out the Minimal Supersymmetric Model (MSSM; e.g. Buchmueller et al. 2014). New limits from direct detection dark matter experiments such as LUX have ruled out a large part of the WIMP mass plus WIMP-nucleon cross-section plane of interest to MSSM (Akerib et al. 2014). Previous claims of WIMP direct detections at ≈10 GeV masses have been comprehensively ruled out by the LUX data. Finally, the idea that new supersymmetric particles may exist at masses of a few hundred GeV is difficult to reconcile with the absence of an electron electric dipole moment at present experimental limits (Hudson et al. 2011; ACME Collaboration et al. 2013).

The ΛCDM model also has well-known astrophysical problems. In particular, the halo mass function increases like a power law towards small scales and looks little like the luminosity or stellar mass functions of galaxies which exhibit a characteristic knee in their distribution at around Milky Way (MW) size. This has to be addressed by feedback from supernovae and/or AGN which keeps the smallest haloes dark (Benson et al. 2003; Baugh et al. 2005; Bower et al. 2006). Star formation feedback is also used to suppress the visibility of subhaloes in the MW which would otherwise overpredict the number of satellite galaxies by more than an order of magnitude. However, these feedback mechanisms may have issues. It has been argued that some of the MW subhaloes are ‘too big to fail’ and so cannot be simply erased by feedback (Boylan-Kolchin, Bullock & Kaplinghat 2011). It has also been argued that although a feedback prescription can reproduce the

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luminosity function of MW satellites their *M/L* and/or their density concentrations may still be incorrect e.g. Zavala et al. (2009). Also the known MW and Andromeda satellites may be found in a planar configuration, difficult to reproduce in a merging model like ΛCDM (Ibata et al. 2013). There have been other claims that dwarf galaxies have cores rather than the cusps predicted by ΛCDM (Moore 1994). Essentially these are all symptoms of the fact that the top-down structure formation of ΛCDM model produces too much power at small scales. However, there are other issues including the lack of merging evident in the evolution of the stellar mass function of even the reddest galaxies.

These problems have led several authors to look at other models such as warm dark matter (WDM) or modified gravity. For example, Lovell et al. (2012) have investigated the possibilities of a 1 keV sterile neutrino. McGaugh (2004) also suggested that a model with $\Omega_\Lambda = 0.97$, $\Omega_b = 0.02$ and $\Omega_\nu = 0.01$ could fit the early *Wilkinson Microwave Anisotropy Probe* (*WMAP*) data. Angus (2009) have suggested that a model with three massless active neutrinos and one 11 eV sterile neutrino and a cosmological constant gives a good fit to the CMB power spectrum. Here, also motivated by the issues for ΛCDM, we further consider the pros and cons of hot dark matter (HDM) models. We start with the low-H_0 baryonic model of Shanks et al. as an example of the 'what you see is what you get' approach in terms of the efforts that have been made to reconcile it to the *WMAP* and *Planck* CMB data.

Thus in Section 2, we therefore describe the low H_0 baryon dominated model of Shanks (1985). In Section 3, we discuss how a cosmological model that assumes a 5 eV mass for each active neutrino species produces a much improved fit to the CMB power spectrum. In Section 4, we shall simulate neutrino universes using GADGET 2 to assess the usual issues for galaxy formation in neutrino models. In Section 5, we shall discuss whether primordial magnetic fields (PMFs) might be able to seed galaxy formation in the neutrino model and in Section 6 we present our conclusions.

2 LOW H_0, BARYON DOMINATED MODEL

Shanks (1985) argued that an Einstein-de Sitter model with a low H_0 would address several problems with a baryon-only model. First, it would allow an $\Omega_b = 1$ model that was compatible with an inflationary $k = 0$ model and with the nucleosynthesis of light element abundances. This is because nucleosynthesis constrains the quantity $\Omega_b h^2$ rather than simply Ω_b. At the time, nucleosynthesis suggested $\Omega_b h^2 < 0.06$ and this meant that if $h < 0.3$ then $\Omega_b \approx 1$ started to be allowed. Secondly, the lower H_0 went the more the hot X-ray gas fills up rich clusters of galaxies like the Coma cluster. The ratio of virial to X-ray gas mass goes as $\approx 15h^{1.5}$ so for $h \approx 0.25$ the virial to X-ray mass ratio reduces to a factor of ≈2. Finally, any Einstein-de Sitter model requires a low Hubble constant so that the age of the Universe remains older than the age of the stars. So at the price of adopting a low H_0, a model with neither dark energy nor exotic particle dark matter would be needed. Of course, distance scale measurements have moved down from 500 to 70 km s^{-1} Mpc^{-1} since Hubble's first measurement.

Unfortunately, the low H_0, $\Omega_b = 1$ model gives a first acoustic peak in the CMB at $l = 330$ rather than $l = 220$. There have been two attempts to move the first peak by smoothing it. Shanks (2007) investigated whether lensing by foreground galaxy groups and clusters might smooth the peak enough to make the smaller scale, high amplitude peaks in the baryonic model fit the larger scale, lower amplitude peaks seen in the CMB data. He found that in principle the peak could be moved but the problem was that the amplitude of foreground clustering had to be 10 × larger than expected from virial analysis of groups and clusters. Sawangwit & Shanks (2010, see alsoWhitbourn, Shanks & Sawangwit 2014) then pointed out that the *WMAP* beam also could have a significant smoothing effect on the CMB peaks. A check on radio sources suggested that the *WMAP* beam could be wider than expected from observations of the planets. Unfortunately, radio sources have too low signal to check the beam profile out to the 1–2 deg. scales which are vital for the position of the first peak. Also before the *Planck* results it was possible to change the first peak position without doing much damage to the other peaks. Since they were being measured by other ground-based experiments it was possible to change the first peak in *WMAP* while maintaining the form of the Silk-damping tail from these other experiments. But *Planck* measures all the peaks simultaneously so it is not possible to move the first peak without smoothing the others away. These problems make it difficult to see how the $\Omega_b = 1$ model can fit the *Planck* CMB data.

The model also has issues with galaxy formation in that Silk damping of the small-scale perturbations means that galaxies take a long time to form. At $z = 0$, the predicted rms mass fluctuation on 8 h^{-1} Mpc scales is $\sigma_8 \approx 0.2$ rather than the $\sigma_8 \approx 1$ seen in the galaxy distribution. Although there are also advantages for a top-down model for galaxy formation it seems that these are outweighed by the difficulties with the CMB and matter power spectra in the baryon dominated model. To escape the difficulties with ΛCDM and the $\Omega_b = 1$ models, we are therefore motivated to look for other alternatives.

3 NEUTRINO MODEL FIT TO THE CMB

We therefore used CAMB (Lewis, Challinor & Lasenby 2000) to investigate a model similar to the baryon dominated model in that, it only uses standard model particles but it assumes a non-zero mass for neutrinos as suggested by various solar neutrino experiments. We searched for combinations of parameters including massive active neutrinos that fitted the *Planck* CMB multifrequency power spectrum (Planck collaboration XV 2013b). If we take $\Omega_b = 0.15$ and $\Omega_\nu = 0.85$ then with $H_0 = 45$ km s^{-1} Mpc^{-1}, this corresponds to the three active neutrinos each having a mass of ≈5 eV. Since the 2σ upper limit from tritium β decay experiments (Aseev et al. 2011) corresponds to 2.2 eV, this 5 eV mass is significantly (≈4.9σ) higher than allowed. The EXO-200 Collaboration (2014) have recently reduced the 2σ upper mass limit for Majorana neutrinos to <0.45 eV. We note that our assumed neutrino mass lies within the $m_{\nu e} < 5.8$ eV 2σ upper limit derived from the SN1987A neutrino detections and that these data may even marginally prefer a mass of $m_{\nu e} \approx 3.5$ eV (Pagliaroli, Rossi-Torres & Vissani 2010). But if the tritium β decay upper limit is confirmed then the neutrinos would then have to be interpreted as sterile rather than active. This model is compared to the *Planck* CMB multifrequency temperature power spectrum (taken from the Planck Legacy Archive file COM-PowerSpect-CMB-R1.10.txt at http://pla.esac.esa.int/pla/aio/planckResults.jsp?) in Fig. 1 where we have kept the optical depth implied by polarization results to $\tau = 0.09$ as in the ΛCDM case. We have similarly assumed $n = 0.96$ for the primordial power spectrum index. For the first three peaks at least, this model is nearly as good a fit as that for ΛCDM, although the fourth, fifth and sixth peaks are generally overestimated by the model. We found that increasing H_0 to 70 km s^{-1} Mpc^{-1} (and hence increasing the mass of each neutrino to ≈13 eV) immediately reduces the height of the second peak and hence also the quality of the fit. Decreasing Ω_ν and increasing Ω_b, although advantageous in

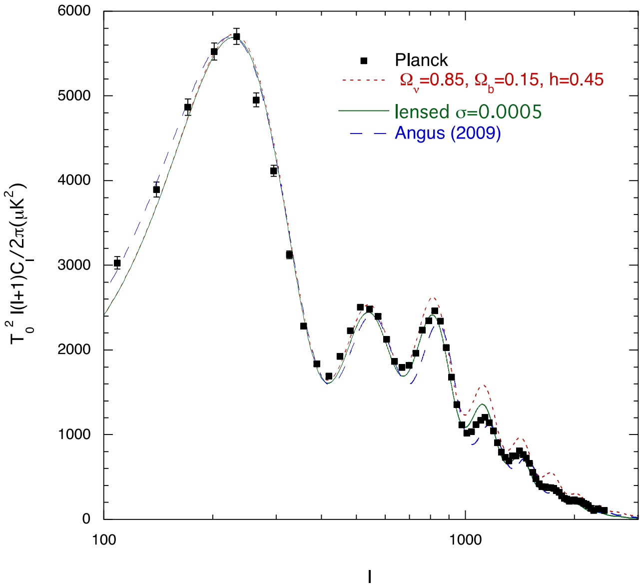

Figure 1. The red dotted line shows the neutrino dominated model with $\Omega_\nu = 0.85$, $\Omega_b = 0.15$, $h = 0.45$ and $n = 0.96$. The green solid line represents the above model now smoothed by lensing using a magnification rms dispersion of $\sigma = 0.0005$. The blue dashed line shows the neutrino dominated model of Angus (2009) with $\Omega_\nu = 0.23$, $\Omega_b = 0.05$, $\Omega_\Lambda = 0.72$ and $H_0 = 71.5\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The models are compared to the *Planck* CMB multifrequency angular power spectrum (Planck collaboration XV 2013b).

moving the neutrino mass smaller, moves the first peak away from $l = 220$ and closer to the $\Omega_b = 1$ value of $l = 330$. Increasing Ω_ν makes the neutrino mass larger and moves the first peak to $l < 220$ while reducing the height of the first peak.

This model may be related to that of Angus (2009) where a CMB fit was obtained assuming an 11 eV sterile neutrino, a cosmological constant and $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. The acceleration in the expansion produced by the cosmological constant reduces the Hubble parameter from $H_0 \approx 70$ to $H_0 \approx 40\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ at $z = 1000$. At the expense of introducing the cosmological constant, the fit to the fourth and fifth CMB peaks is improved. We also investigated the possibility of introducing the cosmological constant and $H_0 \approx 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ into our model with three active massive neutrinos but this provided fits which were slightly less acceptable with the first peak appearing at $l \approx 250$ rather than $l \approx 220$.

Note that the lack of Integrated Sachs Wolfe effect in the Einstein-de Sitter neutrino model means that it fits the $l < 50$ part of the *Planck* spectrum better than either the ΛCDM or the Angus neutrino model. However, the chi-square[1] for our 5 eV neutrino model is significantly higher than for ΛCDM mostly due to the poor fit of the fourth, fifth and sixth peaks. So the neutrino model has a reduced chi-square of $\chi^2 = 126.3$ (121 dof) over the full $2 < l < 2500$ range whereas for $2 < l < 1000$, the reduced chi-square is $\chi^2 = 9.0$ (78 dof). This compares unfavourably to ΛCDM which gives reduced chi-squares of $\chi^2 = 3.8$ in the full range and $\chi^2 = 1.6$ in the low l range. The model of Angus (2009) fares better than the 5 eV neutrino model. In the $2 < l < 2500$ range, this model gives a reduced chi-square of $\chi^2 = 8.6$ and in the $2 < l < 1000$ range the reduced chi-square is $\chi^2 = 2.6$. Thus, it seems that the introduction of a non-zero Λ has significantly improved the fit. However, in a Bayesian sense there is still a significant cost in introducing the improbably small Λ, in both the Angus (2009) and ΛCDM models.

The largest C_l residuals for the 5 eV neutrino model are at $l > 1000$ so these are at least within range of the possible CMB systematics such as lensing and beam profile effects discussed by Shanks (2007), Sawangwit & Shanks (2010) and Whitbourn et al. (2014). The *Planck* power spectrum results agree with those of ACT (Sievers et al. 2013) and SPT (Story et al. 2013) at small scales, making systematics due to *Planck* beam smoothing less likely. Therefore, we concentrate here on smoothing by lensing to improve the fit of the model at small scales. Lensing has been detected in the *Planck* CMB maps at a level comparable with the ΛCDM prediction (Planck collaboration XVII 2013a). Given the uncertainty about how to produce a plausible matter power spectrum from the neutrino model (see below) here, we follow Shanks (2007) and use an ad hoc lensing model based on equation A7 of Seljak (1996). We assume a constant magnification rms dispersion of $\sigma = 0.0005$, a factor of 10 lower than previously used by Shanks (2007) and so closer to the ΛCDM case (see their fig. 3). The results of lensing the neutrino model with this assumed σ are shown in Fig. 1. We see that the fit of the fourth, fifth and sixth peaks are improved, although the fourth peak demands still more smoothing. This is all reflected in the reduced $\chi^2 = 21.4$, down from $\chi^2 = 126.3$ for the unlensed model. Most of the significant residuals still lie at $l > 1000$; when these are excluded the reduced $\chi^2 = 5.8$, down from $\chi^2 = 9.0$. But we must still conclude that formally the neutrino model is rejected and could only be rescued by appeal to an unknown further systematic effect in the CMB data. Meanwhile, the ΛCDM model continues to produce a much better fit over a wide range of scales.

The main further problem that affects both neutrino models is that the predicted matter power spectrum at $z = 0$ lies a factor of 5–6 below the ΛCDM power spectrum (see Fig. 2). Indeed the neutrino model amplitude is little different from the form and amplitude of the $\Omega_b = 1$ model, due to the similar effects of neutrino

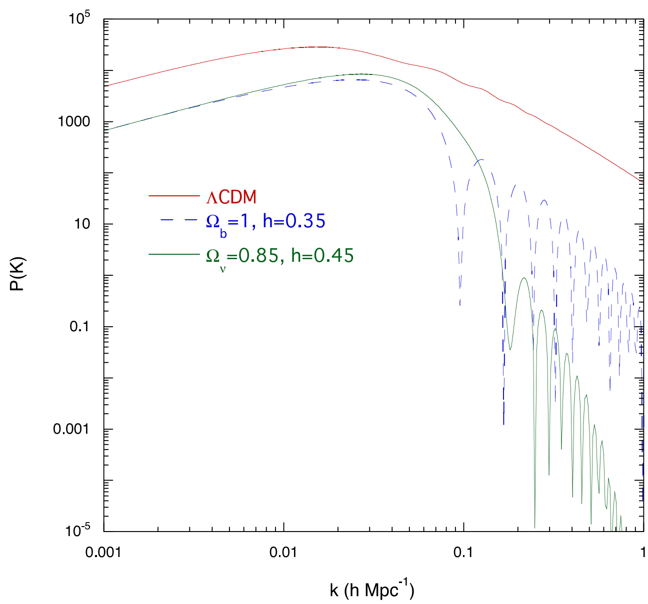

Figure 2. The solid red line shows the matter power spectrum, $P(k)$, predicted by the ΛCDM model. The blue dashed line shows $P(k)$ for the $\Omega_b = 1$, $H_0 = 35\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ model and the green solid line shows the $P(k)$ for our 5 eV neutrino model with $\Omega_\nu = 0.85$, $\Omega_b = 0.15$ and $H_0 = 35\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. All three models assume similar CMB normalizations at large scales.

[1]We have assumed here that the 122 data points are independent. This approximation will be good enough for our purpose of providing a rough goodness-of-fit comparison between the models.

free-streaming and Silk damping. From linear theory, the predicted rms mass fluctuation on 8 h^{-1} Mpc scales is $\sigma_8 \approx 0.2$ again close to the baryon model prediction. This means that the neutrino-dominated model will have the same problem as the baryon-dominated model in that galaxy formation will be too slow. This is the traditional problem for the neutrino model but the improved fit to the CMB data at least relative to the purely baryonic model now motivates us to look for new ways around this issue.

4 NEUTRINO + BARYON SIMULATIONS

We used GADGET-2 to run neutrino model hydrodynamical simulations. Because of the difficulties in setting up free-streaming initial conditions, we simply ran the simulations starting with the linear theory power spectrum at $z = 7$ and running with zero free-streaming. The box size was 150 h^{-1} Mpc on a side with 2×256^3 particles representing neutrinos and gas.

The initial hope here was to build on the work of Bode, Ostriker & Turok (2001), Wang & White (2007) and Lovell et al. (2012) who investigated the appearance of spurious haloes in filaments produced in WDM and HDM *N*-body simulations. These haloes were certainly spurious in that their number depended on the simulation resolution and their origin was traced to discreteness in the grid initial conditions. However, Wang & White (2007) concluded that the growth rate in the filaments must be fast once the filaments form and therefore there is the possibility that if there are any seed fluctuations they might also benefit from this fast filamentary growth rate. One possibility is that if stars can be formed from the gas component then these might form suitable seeds and this directly motivated our decision to run gas hydrodynamic simulations rather than the *N*-body simulations run by the above authors. Otherwise more exotic seeds might have to be considered such as cosmic string wakes (but see Abel et al. 1998; also Duplessis & Brandenberger 2013).

The problem is that with 5 eV neutrinos, the free-streaming scale is around $\approx$50 h^{-1} Mpc at $z \approx 1000$ and this scale is barely non-linear by the present day at least as judged by the galaxy clustering power spectrum. In Fig. 3, we see that a CMB-normalized simulation that produces $\sigma_8 = 0.2$ in the neutrinos at the present day shows little difference in form and amplitude with the linear theory prediction. Therefore, the first difficulty is that non-linear neutrino filaments form very late and in this case gas dynamics and cooling provide little further help in forming galaxies.

We then ran models with enhanced initial amplitudes to give $\sigma_8 = 0.4$, 0.6, 0.8 in the neutrinos by the present day. These simulated power spectra are also shown in Fig. 3. It can be seen that for the $\sigma_8 = 0.6$, 0.8 models, the $z = 0$ power-spectrum slope changes to better match the ΛCDM power spectrum, also shown. We note that in these high amplitude neutrino models, larger halo masses or clusters form earlier and this is more in line with observational data. But the problem remains that the amplitude of rms fluctuations to produce these results is a factor of $\approx 3\times$ larger than implied by the amplitude of perturbations given by the CMB combined with linear theory growth rates. For galaxies to form the extra amplitude must either come from faster growth rates via modified gravity as discussed by Skordis et al. (2006) and Angus (2009) or by introducing 'seeds' as we discuss further below.

5 DISCUSSION

A cosmological model with three $\approx$5 eV active neutrinos gives CMB power spectrum results which are closer to those observed

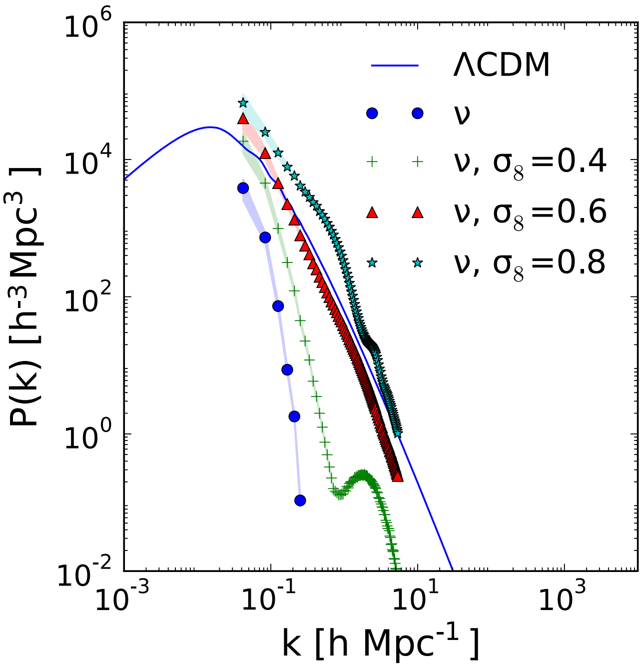

Figure 3. Simulated matter power spectra (and errors) calculated using POWMES (Colombi et al. 2009) from 3×5 eV neutrino simulations made using GADGET-2, starting at $z = 7$. Filled blue circles show a model with initial conditions that produce $\sigma_8 = 0.2$ in the neutrinos by the present day as predicted by linear theory for models normalized to the CMB power spectrum. Green crosses, red triangles and green stars show the effect of increasing the amplitude of the initial power spectrum to give $\sigma_8 = 0.4$, 0.6, 0.8. The blue line shows the standard ΛCDM power spectrum. The results suggest that this neutrino model needs 3× the level of rms perturbations ($\sigma_8 = 0.6$) allowed by the CMB to match the ΛCDM fit to the data at the present day.

by experiments such as *Planck* than e.g. the purely baryonic model of Shanks (1985). But the model still gives a significantly worse fit to the CMB data than ΛCDM and has several other problems. The first is that the model has to assume a low value of Hubble's constant, ($H_0 \approx 45$ km s^{-1} Mpc^{-1}), and higher values near the *HST* Key Project value of $H_0 = 72 \pm 8$ km s^{-1} Mpc^{-1} (Freedman et al. 2001) give much poorer fits. There is also the issue that any Einstein-de Sitter model will be in disagreement with the SNIa Hubble diagram which implies an accelerating expansion of the Universe (Schmidt et al. 1998; Perlmutter et al. 1999; Riess et al. 2001). Both of these issues can be partly addressed if there exists a local underdensity (Keenan, Barger & Cowie 2013; Whitbourn & Shanks 2014). However, this is only able to explain 10 per cent of the $\approx$50 per cent disagreement in H_0. The other part of the discrepancy would have to be explained by issues with the Cepheid and SNIa standard candles, for example, as discussed by Allen & Shanks (2004). Of course, the positive side is that eliminating the accelerating Universe eliminates the fine-tuning problems associated with the cosmological constant or dark energy. Also, the percentage of baryons in the neutrino model is 15 per cent whereas the fraction of baryons in Coma is $\approx$20 per cent with $H_0 = 45$ km s^{-1} Mpc^{-1} so there is no 'baryon catastrophe' here like there was in the standard CDM model where the universal baryon fraction was $\approx$10 per cent and the exotic particle fraction was $\approx$30 per cent (White et al. 1993).

The main problem is that even with the help of the baryons, it is difficult to form galaxies. The free-streaming scale of $\approx$50 h^{-1} Mpc means that superclusters have to be the first structures to condense out of the expansion with galaxies forming in their top-down collapse. Even without free-streaming and the help of gas hydrodynamics, we find that our simulations confirm that with models normalized to the CMB, the rms neutrino fluctuations only reach $\sigma_8 = 0.2$ by $z = 0$. This problem remains unsolved.

We have shown that we need a factor of ≈3–4 increase in the gravitational growth rate to form galaxies in this model. By artificially boosting the initial amplitude of perturbations by this factor, the simulations produce a present-day matter power spectrum much closer to the standard ΛCDM fit to the data. As already mentioned, in top-down structure formation the largest objects are produced first and again this is closer to the ‘down-sizing’ seen in the observations than what ΛCDM models, left to themselves, produce. In the high amplitude neutrino simulations that we ran, the halo mass function also appears closer to the broken power law seen in galaxy luminosity and stellar mass functions than the power-law form produced by ΛCDM.

We considered modified gravity as an approach to increase the growth rate. Angus (2009) in their model with an 11 eV sterile neutrino uses the modified gravity model of Skordis et al. (2006) and claims a good fit to the matter power spectrum. But since we do not need to produce repulsive force at large scales because we do not need to invoke a cosmological constant, this route seems less attractive. Also the limits from redshift space distortion estimates of gravitational growth rates still appear consistent with General Relativity (e.g. Song et al. 2014).

Alternative routes to galaxy formation in the neutrino model include seeding baryon fluctuations in cosmic string wakes. However, Abel et al. (1998) tested this idea using cosmic string in a neutrino model and found that these wakes make little difference to fluctuation growth rates.

More in the spirit of ‘what you see is what you get’ models, we consider seeding by a PMF. Peebles (1980) reviewed the possibilities in a pure baryonic model and following Wasserman (1978) concluded that to obtain $\delta\rho/\rho \approx 10^{-3}$ at decoupling ($z \approx 1000$), the required present intergalactic magnetic field is $\approx 10^{-9}$ Gauss. Given an interstellar magnetic field of $\approx 10^{-6}$ Gauss might correspond to $\approx 10^{-10}$ Gauss if isotropically expanded to present-day IGM densities, then this is in reasonable agreement with what is predicted assuming no amplification by the galactic dynamo effect (Parker 1975) since decoupling. Although in our model with only 15 per cent baryons, the required PMF would need to be correspondingly larger, these order of magnitude arguments may still apply.

Galaxy formation from PMF seeds may look more like a monolithic collapse model than by the mergers that characterize the ΛCDM model. Kim, Olinto & Rosner (1996) made predictions for the matter power spectrum that is produced by PMF. [Note that Shaw & Lewis (2010, 2012) have also made PMF predictions for the CMB and matter power spectra in the context of the ΛCDM model.] Kim et al. (1996) found that in a pure baryonic model the predicted large-scale matter power spectrum was $P(k) \propto k^4$. In this case, the steepness of the matter power spectrum may cause the evolution of the galaxy luminosity and stellar mass functions may be more in line with the pure luminosity evolution/monolithic form frequently seen in the observations (Metcalfe et al. 2001, 2006). Clearly, PMF could also provide an alternative to modified gravity as a route to galaxy formation for the 11 eV sterile neutrino model of Angus (2009).

After this paper was submitted, the BICEP2 detection of large-scale B mode polarization was announced (Ade et al. 2014). If correct, then this result could provide supporting evidence for a PMF (Bonvin, Durrer & Maartens 2014). Note that these authors also suggest that *Planck* CMB non-Gaussianity upper limits from the trispectrum (Trivedi, Subramanian & Seshadri 2014) may indicate that only part of the BICEP2 signal may arise from PMF. Nevertheless, the BICEP2 result is more exactly predicted by the ≈1 nG amplitude expected from PMF rather than the much larger range predicted from primordial gravitational waves and inflation.

Active neutrinos of mass ≈5 eV are compatible with the Tremaine & Gunn (1979) phase-space density upper limit so that such particles can contribute significantly to the dark matter content of galaxy clusters. Angus et al. (2007) also note that neutrinos with a few eV mass are also consistent with the Bullet Cluster observations (Clowe et al. 2006).

Some of the advantages of the previous baryonic model carry through to the neutrino model. Thus, although low-mass neutrinos cannot constitute the dark matter in spiral galaxies due to the Tremaine & Gunn (1979) limit, their flat rotation curves might be explained by a $1/r$ surface density distribution in the disc (Mestel 1963) perhaps due to difficult-to-detect cold gas. The lower baryon density together with the low H_0 are also now more compatible with light element nucleosynthesis. We already noted that the new value of H_0 means that the X-ray gas component is a less massive component of the Coma cluster than in the pure baryonic case and the presence of the neutrinos means that this is not an issue for the model.

However, we also note that the neutrino model would not produce the BAO feature at $z = 0.55$ detected by SDSS DR11 CMASS galaxies (Anderson et al. 2014). First, although the power spectrum does show acoustic oscillations, the peak scale in the correlation function at $z = 0$ would be at $\approx 120\,h^{-1}$ Mpc rather than $\approx 105\,h^{-1}$ Mpc. Furthermore, the low amplitude of the oscillations means that the peak would not be seen in the correlation function at all (see Johnson et al. in preparation). Thus for the neutrino model to evade this constraint, it would have to be argued that the DR11 CMASS BAO peak was subject to bigger systematic and/or random errors than claimed. Johnson et al. are checking the level of rejection of the neutrino model using simple static simulations. If the CMASS errors prove reliable then the Angus (2009) neutrino model may also have problems because it also predicts no BAO peak in the galaxy correlation function.

6 CONCLUSIONS

We have found that a cosmological model with three ≈5 eV active neutrinos produce, at least relative to the previous purely baryonic model of Shanks (1985), an improved fit to the first three peaks of the microwave background power spectrum if a low value of $H_0 \approx 45\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ is assumed. Even here, the model produces a significantly poorer quality of fit than ΛCDM. The model further overestimates the amplitude of the fourth, fifth and sixth peaks but this agreement may be improved by smoothing due to lensing or beam profile systematics (Shanks 2007; Whitbourn et al. 2014). Nevertheless, the neutrino model is formally rejected by the CMB data at $\approx 9\sigma$ significance even when an ad hoc lensing model is applied. This is significantly worse than the fit achieved by ΛCDM. We are here simply recording our view that this neutrino model may be the best that can be done without invoking an exotic new particle or a cosmological constant.

Even ignoring the significantly poorer CMB fit than ΛCDM, the main problem with our neutrino model concerns the difficulty in forming galaxies due to the free-streaming of the neutrinos. The neutrino model provides a matter power spectrum with a turnover at ≈25 h^{-1} Mpc caused by free-streaming which erases fluctuations on small scales. We have concluded that galaxy formation seeds are required for the initial conditions and we have suggested that PMFs may provide such seeds. Such fields can produce a steep matter power spectrum useful for galaxy formation in hot dark matter models. The baryon power spectrum generated by PMF will dominate the power spectrum at small scales. We have noted that such a power spectrum may lead to models more like the monolithic collapse models that the galaxy evolution data favour rather than the merging dominated galaxy formation of ΛCDM. We noted that the BICEP2 claim to detect large-scale B-mode polarization on the CMB may support the existence of PMF. We have also noted that PMF may already have problems evading *Planck* non-Gaussianity upper limits (e.g. Trivedi et al. 2014). PMF at the levels required for galaxy formation in our neutrino model will also be detectable by forthcoming *Planck* CMB polarization results and other seed mechanisms would have to be sought if the required PMFs are confirmed to be ruled out.

There are other problems with the neutrino model. The value of H_0 is low and would require help from a local hole underdensity and other systematic issues with SNIa and Cepheid distances. The matter power spectrum for the model contains baryon acoustic oscillations but these are at too low an amplitude to be compatible with the acoustic peak seen in the DR11 CMASS galaxy correlation function. If the errors on the correlation function are reliable then this would also present a serious problem for any neutrino-dominated model. The 5 eV neutrino masses are compatible with SN1987A upper limits on the neutrino mass (Pagliaroli et al. 2010) but are already ≈5σ above the upper limit from tritium β decay experiments (Aseev et al. 2011). Certainly experiments like KATRIN (KATRIN collaboration 2001) should be able to detect or reject this mass for the electron neutrino at high significance. We conclude that while the inclusion of 5 eV active neutrinos can certainly improve the CMB power spectrum fit compared to a baryon dominated model, the model still produces a less good fit than ΛCDM and this and the other observational problems we have listed illustrate the difficulty in finding acceptable alternatives to the standard ΛCDM cosmology.

ACKNOWLEDGEMENTS

We thank Ashley Ross (ICG, Portsmouth) for useful preliminary discussions on the CMASS DR11 correlation function error analysis. RWFJ acknowledges Durham University for support. JRW acknowledges receipt of an STFC PhD studentship. We also thank an anonymous referee for valuable comments which improved the paper.

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